"III Congreso Latinoamericano de Astrobiología (2021)"
Revista Mexicana de Astronomía y Astrofísica Serie de Conferencias (RMxAC), **55**, 21–25 (2023)

https://doi.org/10.22201/ia.14052059p.2023.55.04

III Latin American Congress of Astrobiology (3CLA)(Virtual-Modality, August 3-6, 2021)
Editors: Leticia Carigi, Sandra I. Ramírez Jiménez, Miguel Chávez Dagostino, and Millarca Valenzuela - DOI: https://doi.org/10.22201/ia.14052059p.2023.55.04

EXTRATERRESTRIAL MATERIAL AND THE EVOLUTION OF THE EARLY LIFE IN THE PRIMITIVE EARTH

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RESUMEN

El conocimiento sobre la química orgánica en nubes moleculares, cometas, meteoritos y sus relaciones crean un límite en los procesos que conducen al origen, evolución y distribución de la vida en la Galaxia. El estudio detallado de las conexiones entre los diferentes tipos de materia extraterrestre y sus componentes orgánicos ayudan a comprender los diversos pasos involucrados en la formación del Sistema Solar y la posible forma en que se pudo haber entregado la materia orgánica primitiva, contribuyendo a los primeros bloques de construcción prebióticos de la vida en la Tierra.

ABSTRACT

The knowledge about the organic chemistry in molecular clouds, comets, meteorites and their relationships create a limit in the processes that lead to the origin, evolution and distribution of life in the Galaxy. The detailed study of the connections between the different types of extraterrestrial matter and their organic components help to understand both the diverse steps involved in the formation of the Solar System and the possible way the primitive organic matter could have been delivered, contributing the first prebiotic building blocks of life to Earth.

Key Words: interplanetary dust — meteorites — micrometeorites — primitive organic matter

1. HISTORICAL ASPECTS

The idea of the contribution of essential elements for the formation and development of life by extraterrestrial sources begins with the first demonstrations by Berzelius (1834) and Wohler & Hornes (1859) on the presence of organics in the carbonaceous chondrites Alais and Kaba. From then on, the efforts of many researchers did not cease in the search for processes capable of synthesizing organic compounds.

All chemical elements such as Fe, Al, Ca, Si, O and also C, are created by nucleosynthesis in stars. The latter behave like nuclear reactors and are involved in the creation of all the chemical elements which contribute to the interstellar medium. It is in that medium where the formation of organic molecules begins. The Solar Nebula, from which the Solar System formed, begins with the fragmentation of a molecular cloud with gas and dust initially rich in organic molecules.

It is very possible that these molecules have not been able to survive the different stages that lead to the formation of planets, such as accretion, impact with other objects, etc., since they all involve highly energetic events with extremely high temperatures. The constant flow of extraterrestrial material to Earth (through meteorites, micrometeorites, etc.) had to face extreme conditions in order to survive the scorching passage through an early Earth's atmosphere.

This organic matter had to be deposited in a suitable environment with the presence of liquid water to develop the first cells with self-reproductive capacities, which, ultimately, could have contributed to the development of life, as we know it today on Earth. Any model that considers the origin of life on the early Earth must take into account three fundamental requirements: 1) Large amounts of liquid water, as the stability of liquid water at the surface of a planet defines a habitable zone (HZ) around a star; 2) Sufficient amount of C and other chemical elements (C, H, O, N, P, S) and 3) An efficient process (e.g., an energy source) to drive biochemical reactions and synthesize pre-biotic organic molecules essential for life (e. g., amino acids, sugars, lipids, etc).

Haldane (1929) published one of the most emblematic hypotheses describing the progressive evolution of matter on the primitive earth constituting a milestone in the history of ideas on the emergence of life. Haldane's ideas came five years after Oparins (Oparin 1924) and their hypotheses are evaluated as

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very similar and therefore their papers are known as the Oparin - Haldane hypothesis.

During the 1950s a new period for the study of the origin of life took place with the first experiments of prebiotic chemistry. In 1953 Stanley Miller tested a hypothesis suggested by Urey (1952) giving rise to one of the best known works. Miller, exposed a primitive terrestrial atmosphere made up of CH_4, NH_3 and H_2 in the presence of liquid water to electric discharges during one week showing the production of amino acids (glycine,-alanine and -alanine) (Stanley & Miller 1953). However, conditions in the Early Earth were extreme not only with an atmosphere composed mainly by reducing gases (CH_3, CH_4, H_2) but exposed to severe ultraviolet radiation that can destroy CH_4 and NH_3 in a short time.

A new model emerged, exobiologists proposed a scenario that took place on the ocean floor, and reconsidered a model initially proposed by Oro (1961) in which comets and meteorites were responsible for contributing organic molecules to the primitive Earth. The identification of amino acids in meteorites and micrometeorites which still fall on Earth today, with a much lower flux to that of the primitive Earth indicate that the arrival of these precursors could lead to the formation of amino acids and of the molecules essential for life.

Here I provide a review of the different types of extraterrestrial materials in which organic matter could have arrived to the primitive Earth and discuss the latest ideas concerning the synthesis and the isotopic variation of the organic matter.

2. METEORITES

Meteorites are rocks and therefore multi-mineral objects that can help us to understand how our Solar System was formed. With an age of more than 4500 Ma (million years) meteorites are the most primitive rocks, as old as the Solar System itself. From the chemical analysis of meteorites in laboratories, it was possible to precisely define the global chemical composition of the Sun, which represents 99.8 % of the matter in the Solar System. Therefore a good analysis of the global composition of our star is all we need to determine an average of the abundances of the elements in the Solar System. Of all the available materials, a special type of meteorite, the CI-type carbonaceous chondrite, was found to have a chemical composition almost identical to the composition of the solar photo-sphere (e.g., (Anders & Grevesse 1989)).

Their petrology, texture and chemistry are used by researchers to classify them into groups. As an initial description of the material that makes up these objects meteorites can be divided in:

1) Stony: are the most abundant meteorites, mainly composed of minerals similar to those of terrestrial rocks and comprise 94 % of the total population.

2) Irons: formed mainly by Fe-Ni, they constitute 5 % of the population.

3) Stony-Irons: made up of a mixture of rocky and metallic material, they represent only 1 %.

Stony meteorites are the most common objects to reach Earth and are divided into two fundamental types:

-Chondrites (undifferentiated meteorites) that contain spherical objects called chondrules and have no equivalent in terrestrial rocks. They are divided into three major classes: carbonaceous (C), ordinary (O), and enstatite (E). The term carbonaceous is a bit confusing because only the CI (e.g., Ivuna), CM (e.g., Murchison), and CR (e.g., Renazzo) chondrites can contain high carbon contents, up to 3% of weight, either in the form of carbonates or of organic compounds.

-Achondrites: (differentiated meteorites) that do not contain chondrules and have a texture similar to terrestrial igneous rocks. They are divided into Primitive achondrites and Differentiated Achondrites. In the later, stony irons, irons and igneous rock fragments from differentiated asteroids and planetary bodies (Mars, Moon) are included.

Each of these groups are subdivided into various categories based on their chemical and isotopic characteristics (see Weisberg, McCoy & Krot (2006), Krot et al. (2014)).

3. ORGANIC COMPOUNDS IN CHONDRITES

Chondrites are characterized by three main components that can be divided taking into account their formation temperatures. Two of these components, the refractory inclusions and chondrules are formed in the solar nebula at very high temperatures ($1400 - 1800\ ^{o}$C) that will prevent survival of organics. The third component is the fine-grained matrix that cements the constituents of chondrites that are formed at low temperature in which the presence of primary organic matter is found. Such matter is normally divided into a macromolecular fraction solvent soluble (SOM) and insoluble fraction (IOM) based on their relative solubilities in typical solvents (e.g., Botta & Bada (2002)).

The IOM of the different chondrites groups is the major organic matter in carbonaceous chondrites and is mainly aromatic and show extremely high

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variations in the elemental and isotopic composition (e.g., Alexander et al. (2007), Alexander et al. (2010)) which are considered to be the result of processes that occurred on the asteroidal parent bodies of the chondrites (e.g., Alexander et al. (2010), Sephton & Botta (2005)).

The SOM in carbonaceous chondrites contain soluble organic molecules in highly variable concentrations ($< 10\ ppm$ to $> 100\ ppm$) that include amino acids, carboxylic acids, purines and pyrimidines, and hydrocarbons. In the CM carbonaceous chondrite Murchison, more than 80 different amino acids have been found however few of them are used by terrestrial organisms (Martins et al. 2007).

4. AN EXTRATERRESTRIAL SIGNATURE

For amino acids, racemic enantiomeric ratios (D/L ~ 1) and high values of Δ^{13}C (from -10 per mil to +40 per mil) as well as D and ^{15}N enrichments will signal their extraterrestrial origin (e.g., (Pizzarello, Huang, & Alexandre 2008), (Martins et al. 2008)). For nucleobases, their stable isotope ratio is essential to demonstrate their non-terrestrial origin (e.g. (Nakamura-Messenger et al. 2006)) and are considered the result of abiotic synthetic pathways in asteroid interiors.

More extreme isotopic enrichments can be found in localized "hotspots", as the organic globules in the Tagish Lake meteorite that resemble cometary carbon, hydrogen, oxygen and nitrogen (CHON) particles and are spherical to irregular organic particles that are often hollow (Elsila et al. 2005). These globules have highly variable H and N isotopic ratios, even in a micrometer scale with all of them having elevated ^{15}N/^{14}N ratios, with Δ^{15}N values significantly exceeding (from 200 per mil to 1000 per mil) the bulk ^{15}N/^{14}N ratios of the Tagish Lake organic matter (77 per mil) (Elsila et al. 2005). Such isotopic anomalies are indicative of mass fractionation during chemical reactions at very low temperatures pointing towards formation of organic globules in the region of the Kuiper Belt or in the cold molecular cloud.

5. INFLUENCE OF SECONDARY PROCESSES

The abundances of polycyclic aromatic hydrocarbons (PAHs) in chondrites appear to have been influenced by secondary processes. In CM2 chondrites a positive correlation is observed between the abundances of PAHs and a more intense aqueous activity. Conversely, the increased metamorphic intensity reduces the abundance of all PAHs (e.g., in CK chondrites) (Glavin et al. 2010). Amino acids in some CM, CI and CR chondrites show L-enantiomeric excesses that appear to increase (up to 20 %) with increasing hydrothermal alteration and therefore be a consequence of such secondary processes (Busemann, Alexander, & Nittler 2007). Also, sputtering processes or UV irradiation that occurred during formation of organic material in interstellar or protoplanetary ices may explain the amorphization of organic matter from the most primitive chondrites as revealed by microRaman spectroscopic studies (Maurette 2006).

6. SMALL EXTRATERRESTRIAL MATTER (1000μ TO 50μ)

Small particles are collected on the Earth's surface either as micrometeorites ($MMs : \sim 20\mu$ to 500μ in size) mainly found in the ice of Antarctica or interplanetary dust particles ($IDPs : < 50\mu$) collected in the lower stratosphere by NASA aircrafts (e.g., Brownlee (1985), Love, & Brownlee (1993)). Micrometeorites (MMs) represent the dominant extraterrestrial matter currently accreted by the Earth ($\sim 4\times10^7 kg/yr$) and represent a total mass of ~ 200 times that of meteorites (e.g. (Duprat, Engrand, Maurette, et al. 2007), (Nesvorny, Jenniskens, Levison, et al. 2010)).

Antarctic MMs together with primitive IDPs are the best representatives of the most primitive interplanetary matter having both an asteroidal or cometary origin. Therefore, MMs and IDPs represent samples of the interplanetary dust of the inner Solar System, of the dust coming from Jupiter-family comets as well as that from the outer part of the Solar System (e.g., the Kuiper Belt and Oort Cloud) (e.g. Poppe (2016), Dobric et al. (2009)).

Comet 81P/Wild 2 samples brought back by the Stardust mission are the only proven cometary material available for analysis on Earth. In terms of chemical, mineralogical, and isotopic compositions, Wild 2 samples are close to carbonaceous chondrites, anhydrous interplanetary dust particles, and micrometeorites (Sandford et al. 2006) . Both, MMs and particles from comet Wild 2 contain polycyclic aromatic hydrocarbons (PAHs) (Matrajt et al. 2004). The amino acid a-aminoisobutyric acid (AIB) is present in about 15 % of the Antarctic MMs in concentrations much higher than in CM meteorites (Cody et al. 2008). Similarly, the carbonaceous matter of Wild 2 samples have atomic N/C and O/C higher than that of primitive meteoritic matter (Messenger et al. 1995).

The organic matter (OM) in IDPs show high D/H and ^{15}N/^{14}N ratios and therefore suggest the presence of interstellar organic molecules (e.g. (Quirico

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et al. 2005)). Micro-Raman studies of IDPs [e.g., Dartois et al. (2013)] show that the first-order carbon D ("disordered") and G ("graphite") bands are the only detected features with spectral characteristics pointing towards a very disordered polyaromatic organic matter with higher spatial heterogeneity either in composition and/or abundances as compared to OM in carbonaceous chondrites (e.g., (Dartois et al. 2013)).

A small fraction of the Antarctic MMs corresponds to the UltraCarbonaceous Antarctic MicroMeteorites (UCAMMs) that are exceptionally organic-rich with large organic matter ($> 1\mu$ in size, (Zhao & Bada 1989)) that is not present in other types of extraterrestrial matter. Their unusually high nitrogen and deuterium abundances led (Zhao & Bada 1989) to propose their formation by energetic irradiations of nitrogen-rich ices in very low temperature regions at the surface of small objects possibly, beyond the trans-neptunian region.

For meteorites, micrometeorites and IDPs the degree of frictional heating during atmospheric entry will define the extent to which organic materials are preserved. However, the presence in the K/T boundary layers (65 million years old), of AIB (aminoisobutyric acid) and racemic isovaline (up to 350 ng/g, (Pizzarello, Huang & Fuller 2004)) indicate the survival of extraterrestrial organic material during impact events.

7. CARBON ISOTOPIC COMPOSITION IN SOM AND IOM

The SOM such as amino acids, nucleobases, and sugars are generally enriched in a heavy carbon isotope (^{13}C) (e.g., (Furukawa, Iwasa, & Chikaraishi 2021)).However, the most abundant organic matter in meteorites, the IOM, is depleted in (^{13}C) (Alexander et al. 2007). The processes responsible for such differences in carbon isotopic composition are not clear. However, the enrichment in ^{13}C in the SOM was invoked to be the result of a contribution of ^{13}C enriched organic compounds formed at very low temperatures distinctive of molecular clouds or the outer-protosolar disk (Furukawa, Iwasa, & Chikaraishi 2021). On the other hand, variations in the isotopic compositions of the IOM between chondrite classes could be related to the existence of isotopically distinct components whose stability might be related to parent body processing (Alexander et al. 2007). Recently, (Rivilla et al. 2021) show that the observed isotopic variations are reproducible in the synthesis of amino acids associated with a formose-type reaction in a heated aqueous solution (80 ^{o}C). Their results indicate that the formose-type reaction simultaneously forms ^{13}C enriched amino acids with (^{13}C) depleted IOM. Therefore, they suggest that organic compounds can be formed without the use of isotopically enriched substrates from the outer Solar System but using substrates commonly present in the early Solar System, in asteroids and the proto-solar disk, in which thermal and photochemical formose-type reaction are possible.

8. THE PLACE OF BIRTH

The recent detection of ethanolamine ($NH_2CH_2CH_2OH$) in a molecular cloud in the interstellar medium (Glavin et al. 2010) indicates that phospholipid precursors can be formed by interstellar chemistry. However, the presence of ethanolamine was reported previously in the meteorite Almahata Sitta (Cody et al. 2008) and suggested to be synthetized in the parent body of this urelite by breakdown of amino acids. Could ethanolamine be formed in interstellar space and be transferred to meteorites later? The fact that (Glavin et al. 2010) found that the proportion of the molecule to water interstellar medium is similar to that found in the urelite strongly supports such a possibility. There are many properties of this organic material that are consistent with an interstellar origin as the isotopic enrichments detected in globules of the chondrite Tagish Lake or those present in the Ultra Carbonaceous Antarctic MMs that confirm their formation in very cold environments, either in the outer Solar System or the protosolar molecular cloud. A detail study of insoluble organic matter (IOM) from carbonaceous, ordinary and enstatite chondrites, found that the observed variations within and between chondrite classes do not correlate with features related either with chondrite formation or with primary features associated with nebular processes (Alexander et al. 2007). The existence of multiple reaction pathways have transformed extraterrestrial organic matter and one of the most significant processes are those that take place in the parent body (Alexander et al. 2007). Extraterrestrial cometary and meteoritic organic matter seems to have the same root. A possible candidate would be complex sugars whose source would be through the formose condensation of formaldehyde, one of the most abundant carbon molecules in the Galaxy. As shown in this review different extraterrestrial materials (meteorites, MMs and IDPs) might have contributed with variable amounts of organic matter (IOM and SOM) to the early Earth. If this matter has transported prebiotic

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seeds formed in the interstellar medium acting as vehicles for the transference of complex molecules during billions of years, this has direct consequences not only in the evolution of primitive life on Earth but in other planets (Mars?) of the Solar System and beyond.

9. ACKNOWLEDGEMENT

I would like to thank the Organizing Committee of the III CLA (Mexico) and the Mexican Astrobiology Society.

REFERENCES

Alexander, C. M., Fogel, M., Yabuta, H., & Cody, G. D. 2007, GeoCoA, 71, 4380

Alexander, C. M., Newsome, S. N., Fogel, M. L., et al. 2010, GeCoA, 74, 4417

Anders E. & Grevesse N. 1989, GeCoA, 53, 197, 214

Berzelius, J. 1834, Phys Chem, 33, 113, 223

Botta, O.& Bada, J. L. 2002, Meteorites Surv. Geophys., 23, 411

Brownlee, D. E. 1985, Cosmic dust: Collection and research. AREPS, 13, 147

Busemann H., Alexander C. M. , Nittler L. 2007, M&PS 42, Nr 7/8, 1387, 1416

Cody, G. D., Ade, H., Alexander, C. M. O., et al. 2008, M&PS, 43, 353, 365

Cody, G. D., Alexander, C. M. O. D., Kilcoyne, A. L. D. & Yabuta, H. 2008, S. Kwok & S. A. Sandford (eds), Organic matter in space (Hong Kong: Cambridge University Press), 277

Dartois, E., Engrand, C., Brunetto, R., et al. 2013, Icar 224, 243

Dobric, E., Engrand, C., Duprat, J., et al. 2009, M&PS 44, Nr 10, 1643, 1661

Duprat, J., Engrand, C., Maurette, M., et al. 2007, AdSpR, 39, 605

Elsila, J. E., de Leon, N. P., Buseck, P. R., & Zare, R. N. 2005, GeCoA, 69, 1349, 1357

Furukawa, Y., Iwasa, Y., & Chikaraishi, Y. 2021, SciA, 7

Glavin, D. P., Aubrey, A. D., Callahan, M. P., et al. 2010, Meteor. Planet. Sci., 10-11, 1695, 1709

Glavin, D. P., Callahan, M. P., Dworkin, J. P., & Elsila, J. E. 2010, M&PS, 45, 1948

Haldane, J. B. S. 1929, The Rationalist Annual, 148, 3, 10

Krot, A. N., Keil, K., Scott, E. R. D., Goodrich, C. A., & Wesiberg, M. K. 2014, Meteorites and Cosmochemical Processes, Volume 1 of Treatise on Geochemistry (Second Edition), Elsevier, 2014 Edited by Andrew M. Davis, p. 1

Love, S. G. & Brownlee, D. E. 1993, Sci, 262, 550

Martins, Z., Alexander, C. M., Orzechowska, G. E., Fogel, M. L. & Ehrenfreund, P. 2007, M&PS, 12, 2125, 2136

Martins, Z., et al. 2008, E&PSL, 270, 130, 136

Matrajt, G., Pizzarello, S., Taylor, S., & Brownlee, D. 2004, M&PS, 39, 1849, 1858

Maurette M. 2006, Micrometeorites and the mysteries of our origins, Berlin: Springer, 330

Messenger, S., Clemett, S. J., Keller, L. P., et al. 1995, Metic, 30 (5), 546, 547

Nakamura-Messenger, K., Messenger, S., Keller, L. P., Clemett, S. J., & Zolensky, M. E. 2006, Sci, 314, 1439

Nesvorny, D., Jenniskens, P., Levison, H. F., et al. 2010, ApJ, 713, 816

Oparin, A. 1924, Moskovskii Rabochii, (in Russian)

Oro, J. 1961, Natur, 197, 971, 974

Pizzarello, S. Huang, Y. Fuller, M. 2004, GeCoA, 68, 4963, 4969

Pizzarello, S., Huang, Y., & Alexandre, M. R. 2008, PNAS, 105, 3700, 3704

Poppe, A. R. 2016, Icar, 264, 369

Quirico, E., Borg, J., Raynal, P. I., Montagnac, G., & Hendecourt, L. 2005, P&SS, 53, 1443, 1448

Rivilla, V. M., Jimenez-Serra, I. J., Pintado, J. M., et al. 2021, PNAS, 118, 22, e2101314118

Sandford, S. A., Aléon, J., Alexander, C. M. O. D., et al. 2006, Sci 314, 1720, 1724

Sephton, M. A. & Botta, O. 2005, IJAsB, 4, 269, 276

Stanley, L. & Miller, G. 1953, Sci, 117, 528, 529

Urey, H. C. 1952, PNAS, 38 (4), 351, 363

Weisberg, M. K., McCoy, T. J., & Krot, A. N. 2006, Lauretta DS and McSween H.Y. (eds.), Meteorites and the Early Solar System II, Tucson, AZ: University of Arizona Press

Wohler M. & Hornes M. 1859, Sitzber. Akad. Wiss. Wein. Math. Naturwiss. Kl, 34, 7, 9

Zhao, M. & Bada, J. L. 1989, Natur, 339, 463, 465